DEVELOPMENT OF REPAIR AND REHABILITATION PLAN FOR CRACK DEFECT IN REINFORCED CONCRETE BUILDINGS IN EKOSODIN COMMUNITY OF OVIA NORTH EAST LGA, BENIN CITY, EDO STATE, NIGERIA.

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PLAGIARISM

This work **DEVELOPMENT OF A REPAIR AND REHABILITATION PLAN FOR CRACKED REINFORCED CONCRETE. A CASE STUDY OF EKOSODIN COMMUNITY, BENIN CITY, NIGERIA** by FELIX, Victory Amiemenoghena with Matriculation Number ENG2002098, of the department of Civil Engineering, Faculty of Engineering, University of Benin City, Edo State, Nigeria has, PASSED the PLAGIARISM TEST.

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CERTIFICATION

This is to certify that this work **DEVELOPMENT OF A REPAIR AND REHABILITATION PLAN FOR CRACKED REINFORCED CONCRETE. A CASE STUDY OF EKOSODIN COMMUNITY, BENIN CITY, NIGERIA** was prepared and compiled by FELIX VICTORY AMIEMENOGHENA, Matriculation Number ENG2002098, of the Department of Civil Engineering, Faculty of Engineering, University of Benin City, Ugbowo Campus, Edo State, in Partial Fulfilment for the Award of the Degree of Bachelor of Engineering (B.Eng), Civil Engineering, Benin City, Edo State, Nigeria.

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DEDICATION

I dedicate this project to Almighty God, whose grace and guidance have brought me this far. Also to my beloved parents, whose unwavering love, encouragement, and sacrifices have laid the foundation for my academic journey, your support has been my greatest motivation.

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ABSTRACT

Reinforced concrete (RC) structures form the backbone of modern infrastructure due to their strength, versatility, and cost-effectiveness. However, over time, these buildings are prone to various forms of deterioration caused by factors such as environmental exposure, poor construction practices, overloading, and lack of proper maintenance. These defects manifest in forms like cracks, spalling, corrosion of reinforcement, and structural deformation, which compromise the integrity and safety of the structure. Hence, this study aim to access the repair and rehabilitation of defective reinforced concrete buildings in Ekosodin Community of Ovia North East LGA, Benin City.

The study Involves conducting a comprehensive review of literature, standards, and case studies to understand the mechanisms of deterioration and the corresponding repair techniques. A detailed site investigation was carried out on selected case study buildings to identify the extent of damage through visual inspection and non-destructive testing methods such as rebound hammer tests. Based on the diagnosis (that is watching out for crack defects only), a repair and rehabilitation plan was developed which incorporates suitable repair materials and structural strengthening method such as bitumen crack injection and stitching as a combined method of repair/rehabilitation.

Visual inspection revealed multiple types of cracks on columns and walls, with widths ranging from 5 mm to 15 mm, attributed to various factors. Rebound hammer results showed that cracked areas had lower surface strength (11–13 N/mm^2) than uncracked regions (24–27 N/mm^2), confirming surface deterioration and validating the rebound hammer test as a reliable tool for assessing concrete integrity prior to selecting suitable rehabilitation methods.

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ACRONYMS

RC - Reinforced Concrete

TEX - Textile Reinforced Mortar

FRP - Fiber-Reinforced Polymer

OSIM - Ontario Structure Inspection Manual

NDT - Non-Destructive Test

UPV - Ultra Sonic Pulse Velocity

HP-FRCC - High-performance Fiber-reinforced Cementitious Composite

SHM - Structural Health Monitoring

CFRP - Carbon Fiber-reinforced Polymer

ASR - Alkali-Silica Reaction

pH - Potential of Hydrogen

GPR - Ground Penetrating Radar

IoT - Internet of Things

MCDM - Multi-criteria Decision Making

ASTM - American Society for Testing and Materials

BIM - Building Information Modeling

UHPC - Ultra-high Performance Concrete

BFRP - Basalt Fiber-reinforced Polymer

ACI - American Concrete Institute

RCB - Reinforced Concrete Buildings

CHAPTER ONE

INTRODUCTION

1.1 Background of Study

Reinforced concrete (RC) is one of the most commonly used construction materials in modern infrastructure due to its durability, strength, and versatility. However, over time, RC structures can become defective due to various factors including environmental exposure, poor construction practices, design errors, overloading, material degradation, or natural disasters like earthquakes and floods. The integrity of these structures, if compromised, poses serious safety risks and economic burdens. Consequently, the rehabilitation and repair of defective RC buildings is a critical area of civil engineering practice aimed at restoring or enhancing the structural performance and extending the service life of such buildings. Building failures in Nigeria are often more frequent and fatal than in many countries, largely because core structural components or codes are overlooked. For example, Lagos alone recorded about 300 building collapses (with ~400 fatalities and 6,000 displaced) from 1978 to 2022, reflecting the grave consequences of RC defects in Nigeria. Studies attribute this to widespread use of substandard materials and construction practices. Orikpete and Ewim (2023), emphasize that the construction industry's "disregard for quality control" has produced many defective structures and rising collapse incidents.

In recent years, the demand for sustainable infrastructure has intensified the focus on repair and rehabilitation rather than complete demolition and reconstruction. According to ACI Committee 562 (2016), proper repair and rehabilitation can extend the service life of concrete structures, reduce life-cycle costs, and minimize environmental impacts. These processes involve identifying the nature and extent of defects, evaluating the structural integrity, and applying appropriate repair methods such as crack injection, jacketing, fiber-reinforced polymer (FRP) retrofitting, and cathodic protection.

Several studies have highlighted the common types of defects in RC buildings. For instance, corrosion of reinforcing steel, often caused by carbonation or chloride ingress, is one of the most widespread and damaging issues (Bhargava et al., 2015). Cracking, spalling, honeycombing, and delamination are also prevalent problems, often linked to improper construction practices and material degradation (Al-Hadithi and Hilal, 2016). Environmental conditions, such as exposure to marine or industrial atmospheres, further accelerate deterioration.

Moreover, structural failures in existing buildings have prompted a more proactive approach toward defect detection and rehabilitation. Non-destructive testing (NDT) methods, like ground-penetrating radar and ultrasonic pulse velocity, are increasingly used to assess damage without compromising the structure (Khatri and Singh, 2019). These assessments guide engineers in selecting suitable and cost-effective repair techniques.

Despite the availability of repair technologies, challenges persist. The effectiveness and longevity of repair methods can vary significantly depending on material compatibility, environmental conditions, and quality of workmanship (Parghi and Suryavanshi, 2018). Additionally, the lack of awareness, inadequate funding, and limited adherence to maintenance schedules have been identified as critical barriers to successful rehabilitation in developing countries (Abubakar et al., 2020).

A growing body of research focuses on rehabilitation techniques such as externally bonded fiber-reinforced polymer (FRP) laminates and near-surface mounted (NSM) FRP systems. These methods enhance flexural, shear, and ductility performance while minimizing disruption to the existing structure. A comprehensive review found FRP retrofits greatly improve structural resilience, though bond performance and durability under environmental stress remain challenges (Naser et al., 2019), (Siddika et al., 2020).

Reinforcement corrosion, driven by carbonation and chloride ingress, is a primary cause of RC deterioration. It leads to loss of bond, reduced steel cross-section and structural cracking, all of which negatively affect seismic capacity (Singh et al., 2023) . To counteract this, coupled strategies targeting corrosion remediation and structural retrofit have been developed. One case study applied micro-concrete jacketing after assessing corrosion loss, restoring seismic performance in a two-storey building (Singh et al., 2023).

Innovative materials have also emerged, such as self-healing concrete using superabsorbent polymers and microfibers has shown up to 90% crack-sealing efficiency, prolonging durability and reducing manual repair needs (Gupta et al., 2017). Moreover, textile-reinforced mortar (TRM) systems offer improved fire resistance and suitability for masonry and RC elements, complementing or replacing Fiber-reinforced polymer (FRP) in certain scenarios (Koutas et al., 2015), (Bournas, 2018).

Despite these advances, limitations persist, FRP systems are prone to debonding, brittleness, and performance degradation under extreme temperatures or harsh chemical environments (Ortiz et al., 2023), (Siddika et al., 2020).

Reinforced Concrete (RC) is a composite construction material in which steel reinforcement (bars or mesh) is embedded in concrete so that the two materials act together under load. In RC, the tensile strength of steel and the compressive strength of concrete synergize to sustain structural stresses. Plain concrete alone cannot readily withstand tensile forces (e.g. bending or seismic loads) without cracking, which is why steel is used.

Defect is an identifiable, unwanted condition in a structure that was not part of the original design intent. For example, corrosion-induced cracking or a construction void would be considered defects. According to Ontario Structure Inspection Manual (OSIM), a defect is "an identifiable, unwanted condition that was not part of the original intent of design". Defects can be of many kinds (cracks, spalls, delamination, etc.) and form the basis for deterioration.

Deterioration is the progression of defects over time. In engineering terms, deterioration refers to a defect that has developed or worsened as time passes. The same inspection manual (OSIM), defines deterioration as "a defect that has occurred over a period of time". For example, a small corrosion pit in rebar that grows into a large rust pocket, or a hairline crack that widens, would be deterioration.

Repair in this context, a repair is the process of fixing a specific damaged element or defect to restore its integrity or function. For instance, patching a spalled concrete beam, injecting resin into a crack, or replacing a corroded rebar segment are repair actions. As a corrosion engineering source explains, concrete repair "is the process of fixing a hardened concrete surface that, over time, has lost the ability to hold the binding concrete materials together due to damage or environmental exposure". The goal is to remedy the defect and restore structural performance (though often not to "like-new" condition).

Rehabilitation is a broader, more comprehensive intervention than a simple repair. Rehabilitation involves working on an entire structure (or significant portion) to restore it to a serviceable state and possibly upgrade it. In engineering practice, rehabilitation is aimed at extending the useful life of a structure. As one source puts it, an asset can be "rehabilitated to bring it close to its original condition and extend its useful life". Rehabilitation typically costs more than a targeted repair but less than full replacement.

This project focuses on understanding the various defects that affect RC buildings and the techniques employed for their effective rehabilitation and repair. The scope encompasses an in-depth study of diagnostic techniques, deterioration mechanisms, repair materials, rehabilitation strategies, and practical methodologies employed in the field.

This study will adopt a systematic approach to assess, diagnose, and propose remedies for defective RC buildings. The key steps include: Conditioned Assessment, Root-Cause Analysis, Selection of Repair and Rehabilitation Methods, Recommendations and Cost Analysis.

1.2 Statement of the Problem

Reinforced Concrete (RC) buildings form a major portion of the built environment in both urban and rural areas due to their structural reliability and economic feasibility. However, many of these structures are increasingly showing signs of distress and deterioration long before the end of their intended service life. Cracks, spalling, corrosion of reinforcement, and deflections are frequently observed in both old and relatively new buildings. These defects not only compromise structural integrity and safety but also result in increased maintenance costs, reduced usability, and, in extreme cases, complete structural failure. Figueroa (2014) found that in East Africa low cement-content concrete was the most common cause of RC building failure, since cement content errors are hard to spot on site. Orikpete and Ewim (2023) found that “inadequate maintenance” in building management is a pervasive root cause of failures. Left unaddressed, defective RC structures can collapse unexpectedly, endangering occupants and neighbors.

The reason for this research Is based on the failure of reinforced concrete buildings which is a pressing issue that requires immediate attention. In Nigeria, for instance, several building collapses have been reported in recent years, resulting in loss of lives and property. These incidents highlight the need for effective rehabilitation and repair strategies to prevent such failures and ensure the safety of lives and properties.

This research answers the question of how defective reinforced concrete buildings can be systematically assessed, repaired, and rehabilitated to ensure structural safety, functionality, and extended service life.

This research solves the problem of lack of standardized procedures and frameworks for identifying, evaluating, and selecting appropriate repair and rehabilitation techniques for defective RC buildings. The frequent application of superficial or unsuitable repairs that fail to restore the structure's durability or load-bearing capacity. The limited practical knowledge among construction professionals regarding modern materials, Non-Destructive Testing (NDT) techniques, and strengthening methods for structural rehabilitation.

While existing literature and codes provide guidance on RC design and construction, there is a noticeable gap in localized, practical knowledge concerning:

1. The integration of Non-Destructive Testing (NDT) methods for accurate defect diagnosis.
2. Cost-effective, durable, and compatible repair materials suited for different types of damage.
3. Case-specific rehabilitation plans based on severity, usage, and environmental exposure.

This project aims to fill this gap by synthesizing technical data, standards, and practical field practices into a coherent guide for engineers and stakeholders involved in building maintenance and rehabilitation.

The ultimate aim of this research is to develop a practical, reliable, and adaptable methodology for the rehabilitation and repair of defective reinforced concrete buildings, which can be used to enhance decision-making in maintenance planning, reduce structural failures, and promote the longevity and safety of our built environment.

1.3 Aim and Objectives

The aim of this work is to develop a repair and rehabilitation plan for selected reinforced concrete buildings in the Ekosodin Community, Ovia North East LGA, Benin City.

The specific objectives are to:

1. Investigate and document the prevalent types of defects in reinforced concrete buildings within the Ekosodin community.
2. Access the primary factors (Causes) contributing to defects in reinforced concrete buildings within the Ekosodin community.
3. Conduct structural assessment to determine the extent of damage and remaining strength of the defective reinforced concrete element, using Non-Destructive Test method (Rebound Hammer).
4. Design comprehensive rehabilitation plan to improve the structural performance and extend the lifespan of the affected building.

1.4 Scope of Study

The scope of this study will include:

1. Identifying the prevalent types of defects (cracks) in reinforced concrete buildings within the Ekosodin Community through inspection and observation.
2. Assessing the primary factors contributing to defects (such as environmental conditions and material quality) by analysing the mechanical properties of concrete from defective reinforced concrete buildings.
3. Evaluating the structural integrity of the concrete samples from the reinforced concrete buildings by conducting Non-Destructive Test (using a Rebound Hammer).

4. Designing a rehabilitation plan based on the identified defects in the reinforced concrete buildings.

1.5. Justification of Study

Reinforced concrete (RC) over time, develop defects due to various factors including environmental exposure, design flaws, poor construction practices, lack of maintenance, and material degradation. This study is justified by the urgent need to address these defects effectively and economically, particularly in developing nations where resources for new construction are limited.

Several researchers have highlighted the growing concern over the structural integrity of aging and defective RC buildings. For instance, Sharma et al. (2021) emphasized that corrosion of reinforcement, cracking, and concrete spalling are the primary causes of deterioration in urban infrastructure, particularly in humid and coastal environments. In their study, they concluded that timely assessment and rehabilitation significantly prolong the service life of structures and reduce the cost of total replacement.

The rationale for this study stems from the need to provide practical and economical solutions for restoring structural functionality and ensuring the safety of RC buildings. Repair and rehabilitation techniques, such as epoxy injection, jacketing, fiber-reinforced polymer (FRP) application, and cathodic protection, have evolved over the years to offer durable and sustainable remediation options (Patel and Desai, 2020). However, the knowledge and application of these techniques remain inconsistent, especially in developing regions.

This research is therefore significant because it seeks to understand, assess, and propose sustainable methods for the rehabilitation and repair of such defective RC buildings. The outcome is expected to reduce the frequency of structural failures, improve safety, extend service life, and promote economic efficiency.

In developing countries such as Nigeria, defects in buildings are common due to poor regulatory enforcement, low construction quality, and harsh tropical conditions (Oyelami and Agbede, 2010). This study fills a critical knowledge gap by providing localized data, evaluating real-life case studies, and developing frameworks suited to tropical and coastal climates.

This study also aligns with the global movement towards sustainability in construction by promoting reuse and life extension of existing infrastructure, as supported by UN-Habitat (2020) in its Sustainable Development Goal 11, making cities and human settlements inclusive, safe, resilient, and sustainable.

Neville (2011), in his seminal work, underscores that deterioration mechanisms such as alkali-aggregate reaction, chloride ingress, and carbonation can significantly reduce the lifespan of concrete structures if not mitigated. He highlighted the importance of timely intervention and notes that proper rehabilitation can restore both structural and functional integrity.

Furthermore, this project supports the global movement towards sustainable construction. As highlighted by Ahmed et al. (2023), rehabilitation of existing buildings aligns with environmental sustainability goals by reducing construction waste, conserving materials, and minimizing carbon emissions associated with demolition and reconstruction.

These authors collectively justify the need for this study by highlighting the technical, economic, and sustainability-related importance of structural rehabilitation. By combining theoretical frameworks with field-based evaluations, this research will help civil engineers, facility managers, and policymakers develop context-specific strategies for building maintenance and preservation.

In summary, based on the foundation laid by these researchers, this study is not only timely but essential. It contributes to ongoing discourse by addressing localized challenges in concrete rehabilitation, exploring cost-effective and durable repair methods, and enhancing the resilience of built infrastructure.

CHAPTER TWO

LITERATURE REVIEW

The durability and performance of reinforced concrete buildings have been extensively studied over the years, especially in the context of structural deterioration, repair techniques and rehabilitation strategies.

2.1 Terms and Definition

Reinforced concrete (RC) refers to concrete in which reinforcement, usually steel bars (rebar), is embedded to carry tensile loads. The integration of steel and concrete allows for composite action, enhancing both tensile and compressive strength (Mosley et al., 2021).

Defective reinforced concrete structures are those that have deteriorated due to various reasons such as poor workmanship, use of substandard materials, improper curing, environmental exposure, or structural overloading. According to Rao and Kumar (2022), defects can manifest as cracks, spalling, honeycombing, or corrosion-induced damage, leading to a reduction in structural integrity and safety.

Rehabilitation refers to the process of restoring a structure to its original or improved state in terms of strength, durability, and functionality. It involves both repair and upgrading works. Patil and Waghmare (2021) defined rehabilitation as a systemic intervention aimed at extending the service life of a deteriorated structure without full replacement.

Structural repair is a corrective process focusing on restoring the load-carrying capacity of a damaged element. According to Shah and Bhavsar (2023), repairs may include crack injection, surface patching, jacketing, and strengthening techniques such as fiber-reinforced polymer (FRP) wrapping.

NDT refers to a range of techniques used to assess the condition of concrete without causing any harm to the structure. Common methods include rebound hammer test, ultrasonic pulse velocity, and ground penetrating radar. Bansal and Arora (2021) state that NDT is critical for diagnosing defects and guiding repair planning.

2.2. Review of Past Work and Research

Prakash and Ramash, (2021) conducted a study on Repair, Rehabilitation and Retrofitting of Reinforced Concrete Structures. This study is a review covering various non-destructive testing (NDT) techniques (e.g. rebound hammer, UPV) and methods such as polymer-modified concrete and guniting. The study emphasizes choosing suitable repair methods based on structural configuration. This study concludes that rebound hammer and ultrasonic pulse velocity (UPV) are effective non-destructive testing (NDT) techniques, while repair methods such as polymer-modified concrete and guniting are suitable options; however, their application must be carefully selected based on the specific condition and configuration of the structure.

Czarnecki, Geryło and Kuczyński (2020) conducted a study on Concrete Repair Durability (Materials). This study shows a comprehensive investigation into the long-term performance of different repair materials and techniques, focusing on their lifespan and environmental resilience. This study concludes that repair durability is largely influenced by the compatibility of materials and the environmental conditions they are exposed to, with long-term performance often compromised in the absence of proper surface preparation and curing; therefore, a lifespan-focused approach to repair design is strongly emphasized.

Di Ludovico and Prota (2020) conducted a study on Repair Costs of Reinforced Concrete Building Components. This study analyzes empirical cost data for RC repairs, and calibrates damage–cost relationships (especially for non-structural elements like infills) under seismic drift and acceleration. This study concludes that empirical damage, cost models have been established, especially for non-structural components, revealing that repair costs increase significantly with seismic drift and acceleration; these findings support cost-based decision-making in post-earthquake repair planning.

Singh et al. (2022) conducted a study on Seismic Analysis and Rehabilitation of Corroded Reinforced Concrete (RC) Building. This study evaluates corrosion-induced deterioration in RC frames, applies seismic assessment via push-over, and devises retrofitting schemes combining Non-Destructive Testing (NDT) and structural strengthening. This study concludes that corrosion significantly reduces the seismic performance of reinforced concrete (RC) frames; however, combining non-destructive testing (NDT) with structural strengthening techniques has been shown to enhance overall performance, with push-over analysis proving effective in optimizing retrofitting schemes.

Bianco (2023) conducted a study on Seismic Rehabilitation of Reinforced Concrete (RC) school buildings using high-performance fiber-reinforced cementitious composite HP-FRCC Jacketing. This study investigates retrofitting inadequately jointed RC school frames by wrapping high-performance fiber-reinforced cementitious composite (HP-FRCC) jackets, following Eurocodes and Italy-specific standards. This study concludes that high-performance fiber-reinforced cementitious composite (HP-FRCC) jacketing significantly improved joint performance and enhanced the seismic resistance of school buildings, while also maintaining compatibility with Eurocode and Italian structural standards.

Shegay et al. (2023) conducted a study on Performance Recovery of a Repaired 4-storey Reinforced Concrete (RC) structure. This study involves experimental shake-table study on a heavily damaged ¼-scale RC building. Epoxy injection recovered approximately 66 % stiffness; full recovery of deformation and damping. System-level recovery quantified. This study concludes that epoxy injection was able to recover approximately 66% of the structure's stiffness, while deformation and damping capabilities were fully restored, demonstrating the effectiveness of epoxy-based approaches for system-level rehabilitation.

Selim, Ibrahim and Emara (2023) conducted a study on Seismic Risk Assessment and Rehabilitation Using Micro-concrete. This study proposes micro-concrete injection for seismic retrofitting of distressed RC buildings, implementing non-destructive and destructive testing to evaluate performance improvements. This study concludes that micro-concrete enhances seismic resilience, with its effectiveness assessed through a combination of non-destructive and destructive testing methods, making it a recommended solution for addressing localized distress in seismic zones.

Gebre Tarekegn et al. (2024) conducted a study on Reliability Assessment of Cracked Reinforced Concrete (RC) Slab by Full-scale Load Test. This study examines a G+4 structure's cracked slab using in-situ load testing; result findings guide pragmatic repair/rehabilitation decisions for active RC buildings. In this study, in-situ load testing has proven effective for evaluating the performance of slabs, enabling targeted repair decisions without the need for full slab replacement, and highlighting the value of real-time, full-scale load testing in active structures.

Al-Mahaidi et al. (2020) conducted a study on Strengthening of Reinforced Concrete (RC) Structures Using Advanced Composite Materials. This study reviewed the use of Fiber Reinforced Polymers (FRPs) and other advanced composites for repairing and retrofitting damaged RC structures. The research highlighted their effectiveness in enhancing flexural and shear strength while offering corrosion resistance and ease of installation. This study concludes that fiber reinforced polymers (FRPs) significantly enhanced the flexural and shear capacity of reinforced concrete elements, while offering durability, corrosion resistance, and ease of installation, making them ideal for rapid retrofitting of damaged RC structures.

Siddique and Khan (2021) conducted a study on Use of Self-Healing Materials for Sustainable Repair of Reinforced Concrete (RC) Structures. The paper explored the application of bacterial concrete and encapsulated healing agents to address micro-cracks in concrete. It emphasized sustainability, reducing maintenance costs, and extending service life of RC buildings. This study concludes that bacterial concrete and encapsulated healing agents effectively seal micro-cracks in concrete, reducing long-term maintenance costs and promoting sustainability by extending the service life of reinforced concrete structures.

Aravinthan et al. (2020) conducted a study on Rehabilitation Strategies for Aging Infrastructure. A case-study-based evaluation of different rehabilitation methods such as jacketing, shotcrete application, and epoxy injection for deteriorated RC structures. The study concluded that method selection must consider structural load, extent of deterioration, and environmental exposure. This study validated the effectiveness of rehabilitation methods such as jacketing and epoxy injection, emphasizing that method selection should be based on load conditions, extent of deterioration, and environmental factors, thereby supporting the adoption of customized rehabilitation strategies.

Gopalakrishnan et al. (2022) conducted a study on Structural Health Monitoring for Reinforced Concrete (RC) Building Repairs. This research presented advanced non-destructive testing (NDT) methods and SHM (Structural Health Monitoring) technologies including ultrasonic pulse velocity (UPV), infrared thermography, and embedded sensors to assess damage and monitor repair effectiveness over time. This study concludes that ultrasonic pulse velocity (UPV), infrared thermography and embedded sensors have proven to be effective tools for structural health monitoring (SHM), enabling continuous damage tracking and significantly enhancing the effectiveness of long-term repair and maintenance programs.

Mourad et al. (2021) conducted a study on Evaluation of Corrosion-Induced Damage and Rehabilitation Techniques in Reinforced Concrete (RC) Members. The paper focused on corrosion in reinforcement as a major defect and assessed various cathodic protection, electrochemical treatments, and concrete patch repair methods. It highlighted the need for combining electrochemical and physical repair strategies for long-term durability. This study concludes that corrosion is a primary cause of failure in reinforced concrete structures, with cathodic protection and patch repair emerging as the most effective solutions; combining electrochemical and physical repair methods further enhances long-term durability.

Prawin et al. (2023) conducted a study on Performance of Retrofitted Reinforced Concrete (RC) Frames Under Seismic Loads. This study investigated the seismic performance of RC frames retrofitted with steel bracings and carbon fiber wraps. Results showed that proper retrofitting significantly enhanced ductility, energy dissipation, and load-bearing capacity during earthquakes. This study concludes that steel bracings and carbon fiber-reinforced polymer (CFRP) wraps were shown to significantly increase ductility and load-bearing capacity, enhance energy dissipation under seismic loading, and demonstrate the effectiveness of hybrid retrofitting strategies for reinforced concrete structures.

Fernandez and Das (2021) conducted a study on Repair vs. Replacement Decision-Making in Defective Concrete Structures. This work proposed a decision-making framework using life cycle cost analysis and structural performance indices to guide whether rehabilitation or demolition-reconstruction is more viable. This study concludes that the proposed framework integrates life-cycle cost analysis with performance indices to identify thresholds beyond which replacement becomes more viable than repair, thereby supporting strategic planning for deteriorated reinforced concrete structures.

Ahmed et al. (2024) conducted a study on Durability-Based Design and Repair of Concrete Structures in Coastal Environments. The study focused on chloride ingress, sulfate attack, and moisture-related deterioration. Emphasized material selection, protective coatings, and environmental monitoring as part of rehabilitation strategy. This study concludes that coastal exposure subjects reinforced concrete structures to chloride and sulfate attacks, making the use of protective coatings and compatible materials essential, while emphasizing the need for environment-specific repair strategies.

Silva, A., et al. (2015) conducted a study on Rehabilitation of Concrete Structures with Fiber-Reinforced Polymer. This study focused on the use of advanced materials like FRP in the repair of RC buildings. It demonstrated effectiveness of FRP in structural strengthening and corrosion resistance. This study concludes that fiber-reinforced polymer (FRP) systems effectively enhance structural strength and corrosion resistance, successfully restoring both flexural and shear capacity, and are well-suited for rapid and durable retrofitting of reinforced concrete structures.

Ghosh, S. (2019) conducted a study on Sustainability of Concrete Structures. This study discussed environmentally friendly repair methods and life-cycle analysis of rehabilitation strategies. It highlighted sustainability as a critical component in modern repair approaches. The study promotes environmentally friendly repair practices, including the use of recycled materials, with life-cycle analysis revealing long-term cost savings, thereby aligning repair strategies with both environmental sustainability and economic efficiency.

2.3. Common Defects in Reinforced Concrete Buildings

These defects may arise during different stages of the structure's life cycle, including design, construction, and service. Understanding the common defects in Reinforced Concrete (RC) buildings is vital for timely rehabilitation and repair.

2.3.1. Cracks in Concrete

Cracking is one of the most frequently observed defects in reinforced concrete. Cracks can occur due to various reasons including thermal movement, shrinkage, overload, corrosion of reinforcement, or poor construction practices. According to Khan et al. (2020), cracks not only affect the visual appearance but also allow the ingress of harmful substances such as chlorides and carbon dioxide, which can accelerate steel corrosion. Cracking can be categorized into structural and non-structural types, with structural cracks posing a more serious threat to the stability of the building.

2.3.2. Corrosion of Reinforcement

Corrosion of embedded steel is a leading cause of deterioration in RC buildings. It often occurs due to carbonation or chloride attack, which reduce the alkalinity of concrete and depassivate the steel reinforcement. As the steel corrodes, it expands, causing cracking, spalling, and loss of bond strength. Uddin et al. (2021) noted that corrosion significantly reduces the load-carrying capacity of structural members, leading to serviceability issues and potential structural failure.

2.3.3. Honeycombing and Voids

Honeycombing refers to the presence of voids within the concrete mass, often due to inadequate compaction or improper mix design. Honeycombs reduce the effective cross-sectional area and durability of concrete. As described by Ahmed and Ali (2022), this defect can lead to water ingress and accelerated deterioration if not addressed during or soon after construction.

2.3.4. Spalling of Concrete

Spalling is the flaking or breaking off of concrete cover, usually due to corrosion-induced expansion of reinforcement, freeze-thaw action, or alkali-silica reaction (ASR). The work of Sharma et al. (2023) highlights that spalling not only reduces the protective cover of reinforcement but also creates safety hazards for occupants due to falling debris.

2.3.5. Alkali-Silica Reaction (ASR)

ASR is a chemical reaction between the alkalis in cement and reactive silica in aggregates, leading to the formation of a gel that swells upon moisture exposure. This can cause expansion and cracking of concrete over time. Singh and Reddy (2021) report that ASR can remain dormant for years before manifesting severe structural damage, often misdiagnosed until significant damage occurs.

2.3.6. Poor Construction Workmanship

Defects arising from poor construction practices include improper concrete placement, inadequate curing, poor quality materials, and misalignment of formwork. According to Thomas et al. (2020), many long-term structural issues can be traced back to lapses during construction. Inadequate curing, for example, leads to surface dusting and poor strength development.

2.3.7. Settlement and Differential Movement

Settlement cracks occur when different parts of a structure settle unevenly due to varying soil conditions or loads. This movement can cause severe cracks in beams, slabs, and columns. Based on the study conducted by Rahman et al.(2020), differential settlement is more common in buildings constructed on expansive or improperly compacted soils and is often exacerbated by poor foundation design.

2.3.8. Ingress of Moisture and Water Leakage

Water leakage is a prevalent defect in RC structures, particularly in basements, roofs, and wet areas. It can result from poor waterproofing, defective joints, or cracks. Prolonged moisture ingress promotes mold growth and accelerates corrosion. Joseph and Daniel (2022), emphasized that effective waterproofing and joint sealing are critical preventive measures.

2.3.9. Inadequate Reinforcement Detailing

Improper detailing or placement of reinforcement can lead to premature failures. Issues such as insufficient cover, improper bar bending, or congestion at joints reduce concrete compaction and increase vulnerability to defects. According to Banerjee and Gupta (2023), design inconsistencies and execution errors in reinforcement layout remain persistent challenges in field applications.

2.4. Causes and Mechanisms of Defects in Reinforced Concrete Buildings

Understanding these defects, their root causes, and deterioration mechanisms is essential for effective rehabilitation and repair;

2.4.1. Poor Construction Practices

One of the primary causes of defects in RC structures is poor construction practices. Inadequate curing, improper concrete mixing ratios, segregation of aggregates, honeycombing, and insufficient compaction lead to weak zones within the concrete mass (Patil and Sawant, 2021). These defects not only compromise strength but also allow aggressive agents to penetrate and deteriorate embedded steel reinforcement.

2.4.2. Design Deficiencies

Design flaws such as inadequate load assessment, improper detailing of reinforcement, and lack of seismic considerations often lead to premature structural issues. A study conducted by Kumar and Singh (2020) highlighted that design errors contributed to over 30% of the structural failures in Indian urban buildings. Such deficiencies exacerbate stress concentrations and lead to cracking or deflection beyond serviceable limits.

2.4.3. Environmental Exposure

Environmental conditions are a significant contributor to deterioration in RC buildings. Chloride-induced corrosion, carbonation, freeze-thaw cycles, and sulfate attacks are major environmental degradation mechanisms. Chloride ions from de-icing salts or marine environments permeate through concrete and depassivate the protective oxide layer on steel, initiating corrosion (Verma and Goyal, 2022). Similarly, carbonation lowers the pH of concrete, exposing reinforcement to corrosion (Rahman et al.,2021).

2.4.4. Material Degradation

The quality of materials used in RC construction greatly affects durability. Substandard cement, contaminated water, or aggregates with high silt content can compromise concrete strength. With aging, concrete undergoes microstructural changes, and the steel may corrode due to ongoing reactions with environmental agents (Singh et al., 2023). Inadequate cover to reinforcement further accelerates degradation.

2.4.5. Load-Related Stresses and Fatigue

Reinforced concrete buildings exposed to cyclic or unexpected loads, such as from earthquakes, traffic, or machinery, develop fatigue-induced cracks and stress concentrations. Over time, these micro-cracks propagate and coalesce, leading to structural damage (Ahmed and Das, 2022). Overloading due to change of building use or vertical expansions without strengthening further contributes to structural stress.

2.4.6. Seismic and Dynamic Effects

Reinforced Concrete buildings not originally designed for seismic loading are prone to failure during earthquakes. Lack of ductile detailing, inadequate confinement, and soft story mechanisms lead to significant cracking, member instability, and even collapse (Mehta and Sharma, 2021). Vibrations from nearby construction, traffic, or industrial operations also cause fatigue and cracking over time.

2.4.7. Water Ingress and Dampness

Water ingress through construction joints, cracks, and porous concrete can lead to internal deterioration. It can cause efflorescence, corrosion of reinforcement, and spalling of concrete (Reddy et al.,2022). Dampness is also a major concern in basements and poorly ventilated areas, encouraging mold growth and compromising indoor air quality.

2.4.8. Chemical Attacks

RC buildings may be exposed to aggressive chemicals in industrial environments or through groundwater. Sulfates, acids, and alkalis react with hydrated cement products, leading to expansion, cracking, and loss of strength. Alkali-silica reaction (ASR), a specific chemical attack involving reactive aggregates, results in gel formation that expands and causes cracking (Choudhary and Patel, 2020).

2.4.9. Corrosion of Reinforcement

Corrosion is arguably the most critical defect mechanism in RC buildings. It is typically initiated by carbonation or chloride penetration and results in rusting of reinforcement, which occupies a larger volume than steel. This expansion induces tensile stresses in the surrounding concrete, causing cracking and eventual spalling (Roy et al.,2023). Corrosion also leads to a reduction in effective cross-sectional area, weakening the structural capacity.

2.4.10. Construction Errors and Workmanship

Improper placement of reinforcement, deviation from specifications, or neglecting construction protocols result in weak zones, misplaced bars, and discontinuities. These defects manifest as cracks, cover loss, and insufficient anchorage, all of which jeopardize structural integrity (Ibrahim et al.,2021).

Figure 2.1: Causes of Deterioration of Reinforced Concrete Structures (Adapted from Bertolini et al., 2013).

Other Causes of Defects include:

a. Lack of Maintenance

Even well-constructed buildings degrade without regular inspection and maintenance. Minor cracks, water leaks, or corrosion signs often go unnoticed until they evolve into major defects (Okoye et al.,2021). Maintenance neglect is a compounding factor that worsens otherwise manageable issues.

b. Fire Damage

Concrete is generally fire-resistant, but extreme heat can reduce the strength of concrete and severely damage steel reinforcement due to spalling and loss of bond (Abdullah and Al-Tamimi, 2021). Post-fire structures may exhibit reduced stiffness, cracking, and disintegration.

c. Biological Growth

In poorly ventilated or damp conditions, moss, algae, fungi, or roots can grow on or in cracks and joints. Over time, biological intrusion can retain moisture, promote corrosion, or even expand cracks mechanically (Zhao et al.,2022).

d. Stray Electrical Currents (Electrochemical Attack)

In some urban or industrial settings, stray currents from grounding systems or nearby electrical installations can lead to accelerated electrochemical corrosion of reinforcement bars (Cárdenas et al.,2021).

e. Thermal Effects (Temperature Variations)

Large or frequent fluctuations in temperature can cause expansion and contraction cycles in concrete, leading to thermal cracking, especially in exposed slabs, bridges, or unjointed members (Wang et al.,2023).

2.5. Condition Assessment and Evaluation Techniques of Defective Reinforced Concrete Buildings

The condition assessment and evaluation of defective reinforced concrete (RC) structures are crucial in ensuring structural safety, longevity, and economic repair strategies. This process encompasses both qualitative and quantitative techniques, including visual inspections, non-destructive testing (NDT), destructive testing, and structural health monitoring, to evaluate the extent and cause of deterioration.

2.5.1. Visual Inspection

Visual inspection is often the first step in the condition assessment of RC structures. It provides preliminary information about surface-level defects such as cracks, spalling, discoloration, corrosion stains, and deformation. According to Ghosh and Roy (2020), systematic visual inspections can categorize damage levels, enabling prioritization of further detailed investigation.

Recent developments have integrated drone-based inspections and AI-assisted crack detection to improve accuracy and efficiency (Elhattab et al., 2022). These technologies are especially beneficial in assessing hard-to-reach areas and minimizing the need for scaffolding or manual labor.

2.5.2. Non-Destructive Testing (NDT) Methods

NDT techniques are widely used for in-depth evaluation without damaging the structure. Commonly used methods include:

Rebound Hammer Test (Schmidt Hammer) is used to estimate surface hardness and, indirectly, compressive strength, Kumar et al., (2021) validated this method as effective for quick assessments, though it has limitations with surface carbonation and moisture content.

Ultrasonic Pulse Velocity (UPV) assesses internal flaws such as voids and cracks by measuring the speed of ultrasonic pulses through concrete. According to Singhal and Srivastava (2023), combining UPV with rebound hammer results yields more reliable estimates of concrete quality.

Half-Cell Potential Measurement is used to detect corrosion activity in embedded reinforcement. This electrochemical method was highlighted by Das et al.,(2020) as a reliable predictor for corrosion probability zones in reinforced concrete members.

Ground Penetrating Radar (GPR) helps in mapping embedded rebar, voids, and delaminations. It has gained popularity due to its high-resolution data and real-time feedback (Patil et al., 2021).

2.5.3. Destructive Testing

Destructive methods, although limited in application due to invasiveness, provide accurate strength and material composition data. Core extraction and laboratory compressive strength tests remain the gold standard for validating NDT results. According to Naidu and Kumar (2020), destructive testing should supplement NDT in cases where critical decisions (e.g., demolition vs. repair) are needed.

2.5.4. Structural Health Monitoring (SHM)

SHM systems use embedded sensors to provide real-time data on the structural behavior of RC buildings. These sensors monitor parameters like strain, temperature, crack width, and vibrations. The integration of Internet of Things (IoT) in SHM has revolutionized the field, allowing remote condition monitoring and predictive maintenance (Chen et al., 2023). Fiber optic sensors and wireless sensor networks are gaining traction due to their accuracy and minimal invasiveness. According to Zhang and Liu (2022), such systems can detect early-stage degradation, thus optimizing repair timing and reducing life cycle costs.

2.5.5. Condition Rating and Structural Assessment Frameworks

Based on the gathered data, a condition rating system is applied to quantify the structure's health. International standards like ASTM C876 (for corrosion) and IS 456:2000 provide guidelines for interpreting test results. (Mishra et al., 2021) proposed a multi-criteria decision-making (MCDM) framework integrating visual and NDT data to prioritize repair interventions in aged RC structures.

Additionally, Building Information Modeling (BIM) is increasingly used to document and visualize defects, maintenance history, and predictive degradation models, offering a centralized platform for decision-making (Ahmed et al., 2023).

2.6. Repair Materials and Techniques of Defective Reinforced Concrete Buildings

The rehabilitation and repair of defective reinforced concrete (RC) structures is a critical aspect of civil engineering, ensuring the safety, durability, and functionality of buildings that have deteriorated due to various factors such as corrosion, structural overload, poor workmanship, or environmental exposure. This write-up explores the modern repair materials and techniques utilized in addressing deficiencies in RC buildings, with reference to current research and professional practices.

2.6.1. Causes of Defects in Reinforced Concrete

Before selecting appropriate repair techniques, understanding the root causes of defects is essential. Common issues include corrosion of reinforcement, cracks due to shrinkage or overload, spalling, honeycombing, and poor concrete compaction. According to Akinyemi et al. (2021), chloride-induced corrosion and carbonation are among the most prevalent causes of steel reinforcement deterioration in tropical environments.

2.6.2. Selection Criteria for Repair Materials

Repair materials should be compatible with the existing substrate in terms of thermal expansion, modulus of elasticity, and chemical composition. Additionally, they must offer durability, ease of application, and bonding strength. As noted by Al-Mahaidi and Mirmiran (2020), selecting materials that do not introduce new stresses or incompatibilities into the structure is vital for long-term performance.

2.6.3. Repair Materials

a. Cementitious Materials

Cement-based repair mortars are widely used for patch repairs, crack filling, and surface leveling. Polymer-modified mortars have enhanced bonding and reduced permeability (Anagnostopoulos et al., 2022), highlighted their application in moderate exposure conditions, emphasizing their economic advantage and ease of use.

b. Epoxy Resins

Epoxy-based materials are used for crack injection, bonding, and surface protection. Their high tensile strength and chemical resistance make them suitable for structural repairs, especially in load-bearing components. However, they are brittle and sensitive to temperature variations (Zhou and Zhang, 2021).

c. Fiber-Reinforced Polymers (FRP)

FRP composites, including carbon, glass, and aramid fibers, are increasingly used for strengthening and retrofitting RC structures. They provide high strength-to-weight ratios and are non-corrosive (Wang et al., 2023), reported successful applications of externally bonded carbon fiber-reinforced polymer (CFRP) sheets for flexural strengthening of RC beams.

d. Microbial Concrete and Self-Healing Materials

Emerging technologies such as bacterial-based self-healing concrete are being investigated for their ability to autonomously seal cracks and restore strength (Ghosh et al., 2020), demonstrated that Bacillus subtilis-based concrete showed significant crack healing within 28 days.

e. Corrosion Inhibitors

To prevent further degradation of reinforcement, corrosion inhibitors are often applied as coatings or added to repair materials (Li and Song, 2021), discussed the efficiency of migrating corrosion inhibitors in extending the service life of repaired structures.

2.6.4. Repair Techniques

a. Crack Injection

This method involves injecting epoxy or polyurethane resins into cracks under pressure to restore structural integrity. It is effective for narrow cracks in structural elements (Zhang et al., 2020), demonstrated its use in restoring load-carrying capacity in RC girders.

b. Surface Coating and Reprofiling

Surface coatings like acrylics, polyurethanes, and cementitious overlays are used for protection against moisture ingress. Reprofiling involves reshaping damaged concrete sections with repair mortars. As reported by Singh and Bhattacharjee (2021), surface protection significantly reduces carbonation depth.

c. Jacketing

Jacketing with concrete, steel, or fiber-reinforced polymers (FRP) wraps increases load-bearing capacity and stiffness of columns and beams. This technique is widely used in seismic retrofitting. According to Alam et al. (2022), carbon fiber-reinforced polymer (CFRP) jacketing showed substantial improvements in ductility and shear resistance.

d. Cathodic Protection

This electrochemical technique prevents corrosion by making the steel reinforcement the cathode of an electrochemical cell. It is suitable for structures in aggressive environments (El Maaddawy and Soudki, 2020), documented its long-term effectiveness in marine structures.

e. Grouting

Grouting is employed to fill voids or delaminated areas using cementitious, chemical, or epoxy-based grout. This restores continuity and stiffness in elements like slabs and beams (Park et al., 2023), demonstrated the use of polyurethane grout in waterproofing RC tunnels.

2.7. Rehabilitation Strategies and Methods of Defective Reinforced Concrete

The rehabilitation of defective reinforced concrete (RC) structures has become a crucial aspect of civil engineering due to aging infrastructure, environmental effects, and increasing load demands. The strategies adopted vary based on the type and extent of damage, functional requirements, and economic constraints.

2.7.1. Assessment of Defects

Effective rehabilitation begins with a thorough assessment of the defects in the structure. Non-destructive testing (NDT) methods such as Ground Penetrating Radar (GPR), ultrasonic pulse velocity, and rebound hammer tests are commonly used (Zhou et al., 2020). These methods help identify issues such as honeycombing, corrosion of reinforcement, delamination, and cracking.

2.7.2. Classification of Defects

Defects in RC structures are typically categorized as structural and non-structural. Structural defects, such as loss of load-bearing capacity, require urgent attention, while non-structural defects, like surface cracks, mainly affect aesthetics (Cheng et al., 2021).

2.7.3. Rehabilitation Strategies

a. **Surface Repair Techniques:** Cracks and spalls are often treated using epoxy injection, polymer-modified mortar, or shotcrete. Epoxy injection is particularly effective for narrow cracks that require structural bonding (Singh and Bansal, 2020).

b. **Corrosion Mitigation:** Reinforcement corrosion is one of the leading causes of deterioration. Techniques such as cathodic protection, use of corrosion inhibitors, and application of protective coatings are commonly employed (Koleva and Van Breugel, 2021).

c. **Structural Strengthening:** It restores or enhances the load-carrying capacity of structures, methods such as fiber-reinforced polymer (FRP) wrapping, steel plate bonding, and section enlargement are used. FRP composites, due to their high strength-to-weight ratio and corrosion resistance, are increasingly favored (Zhao et al., 2022).

d. **Grouting** is used to fill voids and cracks in concrete. Cementitious or chemical grouts are selected based on the width of cracks and the structural requirement (Verma et al., 2021).

e. **Concrete jacketing** involves adding a new layer of reinforced concrete around existing columns or beams to enhance strength and ductility. This method is particularly useful in seismic retrofitting (Sarkar and Reddy, 2023).

f. **Use of Ultra-High Performance Concrete (UHPC)** overlays and patches have shown excellent performance in terms of durability and bonding with existing concrete surfaces (Li et al., 2022).

2.7.4. Monitoring and Maintenance

Post-rehabilitation monitoring ensures the effectiveness of repair works. Structural health monitoring systems and periodic inspections help in detecting any further deterioration early (Nguyen et al., 2023).

In conclusion, the rehabilitation of defective RC structures demands a comprehensive understanding of defect causes, suitable material selection, and methodical execution of repair techniques. As research advances, the integration of smart materials and AI-based monitoring is expected to redefine the rehabilitation landscape.

2.8. Innovative Repair Materials and Methods

Alasmari et al., (2025) investigated the rehabilitation of damaged RC beams using carbon fiber-reinforced polymer (CFRP) laminates and high-strength concrete incorporating recycled tire steel fibers. Their study demonstrated improved structural performance and sustainability.

Ashteyat et al., (2024) explored the use of basalt fiber-reinforced polymer (BFRP) bars and carbon fiber-reinforced polymer (CFRP) ropes and strips to repair RC beams subjected to high temperatures. The near-surface mounted technique employed showed significant restoration of structural integrity.

2.9. Research Gaps

Despite the advancement in previous research and studies of repair and rehabilitation of defective reinforced concrete structures, several gaps remain, because most studies/research focused on foreign context of repair and rehabilitation, while adhering to foreign construction practices (without considering specific context and construction practices in local regions), some studies also focused on the use of single materials (either Bitumen or Stitching only) for repair and rehabilitation of crack defects in reinforced concrete structures, without considering the use of a combination of materials, some studies did not carry out performance verification after repair and rehabilitation, while some studies emphasized on advanced monitoring technologies but overlooked low-cost and portable non-destructive testing (NDT) tools suitable for use in developing countries for small-scale projects.

This study intends to address these gaps, by focusing on local specific context and construction practices, specifically within the Ekosodin Community, located in Ovia North-East Local Government Area of Benin City, Edo State, Nigeria, by conducting a quantitative assessment of reinforced concrete buildings both before and after rehabilitation. This incorporates the use of innovative materials and techniques, specifically a combined method of bitumen crack injection and stitching, providing step-by-step repair workflows for the effective rehabilitation of cracks in defective reinforced concrete structures.

3.2.1. Identification of Cracks Defects in Reinforced Concrete Buildings

Cracks are among the most common and visually evident defects in reinforced concrete (RC) structures. Crack identification is a critical step in the diagnosis and rehabilitation of reinforced concrete (RC) buildings. The presence of cracks, whether structural or non-structural, often signals distress in the concrete and must be properly evaluated to determine their cause, severity, and impact on structural integrity. Early and accurate identification of cracks is essential to ensure safety, durability, and effective maintenance of RC structures.

3.2.1.1 Preliminary Crack Survey and Classification

This aspect will involve field work, it will comprise of;

a. Visual Inspection

Visual inspection is the most common and first step in identifying cracks. It involves the direct observation of surfaces to detect crack patterns, locations, widths, and orientations. Tools like crack width gauges, magnifying lenses, and measurement tapes are often used to estimate crack size and monitor changes over time. This method is cost-effective and simple, but it relies heavily on the experience of the inspector and is limited to surface-level defects.

b. Crack Classification

Crack classification helps to evaluate the severity and likely cause of cracking. Cracks can be categorized based on their width, direction, pattern, and cause.

Classification will be done according to ACI 224R:

Type I: Shrinkage/hairline cracks (<0.3 mm)

Type II: Structural cracks (0.3–1 mm)

Type III: Wide/active cracks (>1 mm)

Bitumen injection plus stitching primarily were used for Type II and III structural cracks.

The cracks identified so far from 12 different reinforced concrete buildings in Ekosodin Community of Ovia North East LGA, Benin City, Edo State were not greater than 15 mm (1.5 cm).

c. Non-Destructive Testing (NDT)

This method complement visual inspection by providing information about subsurface or hidden cracks without damaging the structure. Techniques such as Ultrasonic Pulse Velocity (UPV) help detect internal voids or discontinuities, while Rebound Hammer tests estimate surface hardness.

3.2.1.2 Objective of Rebound Hammer Test

The objective of the rebound hammer test is to determine the relative surface hardness of concrete at selected points on the structure and to estimate the corresponding compressive strength. This enables a comparative assessment between cracked areas and sound (uncracked) areas of the reinforced concrete building.

3.2.1.3 Equipments Used

Rebound (Schmidt) Hammer (properly calibrated)

Wire brush and grinding stone

Measuring tape

Marker or chalk for marking test points

Data recording sheet

3.2.1.4 Selection of Test Locations

To obtain representative and comparative data, test points were selected on two(2) distinct surface conditions of the reinforced concrete columns:

a. Cracked Area

Readings were not taken directly on the crack line but at points around the crack, typically 25–100 mm away, to assess the concrete condition adjacent to the defect.

b. Uncracked (Sound) Area

Readings were taken on the portions of the same member or similar structural element showing no signs of cracking or distress, to serve as a baseline for comparison.

3.2.1.5 Surface Preparation

Each selected test area was properly prepared by:

a. Cleaning

Cleaning the surface using a wire brush to remove dirt, dust, laitance, or loose particles, because a clean surface is crucial, especially for Non-Destructive Test (NDT) methods that rely on surface contact. This step ensures clear access to the concrete and accurate signal transmission during testing.

b. Grinding

Grinding slightly rough surfaces to ensure uniformity and proper contact of the hammer plunger.

c. Dry Surface

Ensuring that the surface was dry.

3.2.1.6 Rebound Hammer Test Procedure

a. The rebound hammer was held firmly and perpendicular to the concrete surface (or at the desired angle), ensuring full contact between the plunger and the surface.

b. The plunger was pressed gradually until the hammer impacted the surface, and the rebound number (R-value) was recorded.

c. At each test location, a maximum of 5 readings were taken within a small area (not less than 25 mm apart).

d. The mean of the values was computed to represent the rebound number for that test point.

e. The same procedure was repeated for all selected locations on cracked and uncracked regions.

3.2.2 Measures for Mitigating Cracks in Reinforced Concrete Buildings Using Bitumen Injection plus Stitching as a Combined Method of Rehabilitation

The cracks considered as a structural defects to be identified in this study were mitigated using a combined rehabilitation method of bitumen injection and stitching, which consist of the following steps;

1. Bitumen Crack Injection

This step comprises of;

a. Material Selection

The selection of bitumen-based injection material depends on the type and width of the crack, exposure conditions, and structural requirements. Bitumen emulsions or modified bitumen products are preferred for their waterproofing properties, flexibility, and ease of application. The material should have good adhesion, low viscosity (to penetrate fine cracks), and high resistance to environmental degradation.

b. Injection Port Installation

Injection ports (or packers) are fixed along the length of the crack to allow controlled entry of the bitumen. Ports are typically spaced 200–300 mm apart, depending on crack length and accessibility. Before installation, the crack surface is cleaned, and ports are secured using epoxy or similar bonding agents. Proper placement ensures even distribution of the injection material and prevents leakage during the process.

c. Injection Procedure

Once the ports are in place and the surface is sealed, the bitumen is injected under pressure using specialized pumps. The process usually starts from the lowest port (in vertical cracks) to ensure complete crack filling and displacement of air and moisture. Injection continues until bitumen is observed exiting from the next port, which is then sealed off and the process repeated sequentially. The goal is to achieve full-depth filling of the crack.

d. Port Removal and Surface Finishing

After the injection material has cured or set, the ports are carefully removed. The holes are patched with mortar or epoxy filler, and the surface is leveled and finished for aesthetics and protection. In exposed areas, surface painting or waterproofing membranes may be applied as a final protective layer.

2. Stitching of Cracks

After the injection of bitumen, the next step stitching of cracks follows immediately, using rebars. Stitching is a structural crack repair technique used to restore integrity and prevent further movement across cracks in reinforced concrete (RC) building. The method involves embedding metal bars ("stitch bars") across the crack to hold the concrete together, much like sewing fabric. It comprise of;

a. Stitch-bar Preparation

Stitch-bars, typically made of stainless steel or high-strength steel, are cut to size (6-8 mm diameter and 200-300 mm long) and prepared for installation. The bars are often coated with epoxy or corrosion-resistant material to enhance bonding and protect against future corrosion. Their length and diameter depend on the depth of the crack and structural requirements. Surface roughening or de-scaling may also be done to ensure proper grip.

b. Drilling Cross-holes

Cross-holes are drilled perpendicular to the crack, spanning both sides of the damaged section. These holes are usually spaced at regular intervals and aligned to accommodate the stitch-bars. Care is taken to ensure the holes are deep enough for proper anchorage but not so deep as to damage existing reinforcement. Dust and debris are cleaned from the holes before inserting the bars.

c. Bar Grouting

Once the bars are inserted into the cross-holes, they are fixed in place using a high-strength, non-shrink grout or epoxy resin. The grout ensures that the bars are tightly bonded to the surrounding concrete and able to transfer tensile loads across the crack. Proper curing of the grout is critical to achieving the desired structural performance.

d. Surface Restoration

After grouting, the crack and surrounding area are patched with repair mortar or epoxy filler to restore surface continuity and protect the embedded bars. Finishing may involve smoothing, painting, or applying a waterproofing coat to match the existing concrete and improve durability. This step also enhances the visual appearance of the repaired surface.

3.2.3. Quality Control and Monitoring

Effective repair of cracks in reinforced concrete (RC) structures does not end with the application of materials or techniques. Ensuring long-term performance requires continuous quality control and monitoring to verify the success of repairs, detect any recurrence of damage, and maintain structural safety. Key methods in this process include;

a. Post-repair Inspection

Post-repair inspection involves a thorough visual and technical evaluation of the repaired area to confirm that the cracks have been fully treated and the structural integrity has been restored. This includes checking for:

i. Complete filling of cracks (especially in injection or stitching methods)
ii. Proper curing of repair materials
iii. Alignment, surface finish, and any signs of re-cracking

iv. Conformance to design and material specifications

Qualified inspectors may also use non-destructive testing (NDT) tools, such as ultrasonic devices or rebound hammers, to assess the internal soundness of the repair.

b. Instrumented Monitoring

Instrumented monitoring provides quantitative data on the performance of repaired cracks over time. This involves installing sensors or monitoring devices, such as; crack width gauges (manual or digital), strain gauges to measure deformation across the crack zone and displacement sensors or data loggers for long-term tracking.

Such instrumentation allows engineers to monitor changes due to thermal effects, loading, or environmental conditions and helps identify early signs of failure or continued movement.

c. Documentation

Proper documentation is critical for tracking the history, methods, and results of crack repairs. A comprehensive record includes; pre- and post-repair photographs, repair techniques used and materials applied, test results and monitoring data, Inspection checklists and approval notes and maintenance schedules or follow-up plans.

This documentation serves as an essential reference for future evaluations, legal compliance, and asset management.

3.2.4. Health, Safety and Environmental Considerations

Combining bitumen injection and stitching provides a comprehensive solution for repairing cracks in reinforced concrete buildings, addressing both moisture-related and structural deficiencies. When using bitumen injection and stitching together for crack rehabilitation in reinforced concrete buildings, it is essential to consider health, safety, and environmental (HSE) factors. Workers must wear proper protective gear such as gloves, goggles, and masks, especially when handling hot bitumen and chemical grouts. Adequate ventilation is necessary to prevent inhalation of harmful fumes, and care should be taken when operating high-pressure pumps or drilling equipment to avoid injury. Fall protection and safe handling procedures are also critical on elevated work areas.

From an environmental standpoint, all materials, especially leftover bitumen, grout, and cleaning agents should be disposed of properly to avoid contamination. Measures should be in place to prevent spills, control dust and noise, and minimize emissions. Using environmentally friendly, low volatile organic compounds (VOC) materials can further reduce the environmental impact. Overall, integrating proper health, safety and environmental (HSE) practices ensures that the repair process is safe for workers and sustainable for the surrounding environment.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the results obtained from the visual inspection and non-destructive testing (NDT) carried out on selected reinforced concrete building elements showing visible crack defects. The discussion interprets the findings in relation to the concrete's in-situ strength, extent of deterioration, and probable causes of cracking. In addition, the chapter highlights the implication of these results on the proposed repair and rehabilitation method, specifically the combined use of bitumen injection and stitching.

4.2 Results of Visual Inspection: Prevalent Types of Defects in RCB Structures within Ekosodin Community

Visual inspection was the first step in assessing the condition of the reinforced concrete elements. The inspection revealed various types of cracks in columns and walls of 12 different building in Ekosodin Community of Ovia North East, Benin City, Edo State, Nigeria, with most cracks ranging between 0.5 cm to 1.5 cm (5 mm to 15 mm) in width.

The cracks observed were predominantly vertical and diagonal, extending through the concrete cover of the columns, and in most locations, extending through to the wall, an indication of moisture ingress.

3.	Fine vertical crack at Wall-column interface	3	Non-Structural	Temperature Variations or Drying Shrinkage (Bourdin et. al, 2013; Neville, 2011)
4.	Thin crack along Column -wall joint	2	Non-Structural	Differential Movement (Golewski, 2023)
5.	Fine Vertical crack along the wall	5	Non-Structural	Shrinkage of Mortar or Concrete (Aktan, 2004)
6.	Vertical crack along a column	3	Structural	Overloading or Excessive Axial Stress (Alasmari, 2023)
7.	Diagonal crack at junction of wall, at corner of building	3	Structural	Uneven Settlement of Foundation (Zhao and Dong, 2011)
8.	Severe Diagonal or Vertical cracks on a column	2	Structural	Overloading or Structural Overstress, Corrosion of Reinforcement (Aldella et.al, 2022)

From the visual assessment, it was evident that most of the cracks in the reinforced concrete buildings were structural, it implies that the buildings are under significant structural distress, the load-bearing capacity, durability, and safety are compromised, and the buildings requires immediate detailed assessment and rehabilitation by structural engineers.

4.3. Results from Rebound Hammer Test: Structural Integrity of Reinforced Concrete Columns.

The rebound hammer test was performed to evaluate the surface hardness and estimate the compressive strength of the cracked and uncracked concrete surfaces.

The test was conducted on two defined zones for each affected member:

Zone A: Around the crack surface (approximately 20–100 mm from the visible crack)

Zone B: Uncracked/sound region (control area)

4.3.1 Results from Rebound Hammer Test

The values obtained from the Non-Destructive Test using the Rebound hammer are presented in Table 4.2.

Table 4.2: Results from Rebound Hammer Test

Site Location	Test Zones/Locations	Average Rebound Values	Compressive Strength (N/mm²)
1.	Downstairs Zone A (Around Cracked Zone)	22	11
	Downstairs Zone B (Uncracked/Sound Zone)	30	26
2.	Downstairs Zone A (Around Cracked Zone)	21	12
	Downstairs	30	26

	Zone B (Uncracked/Sound Zone)		
3.	Downstairs Zone A (Around Cracked Zone)	21	12
	Downstairs Zone B (Uncracked/Sound Zone)	31	27
4.	Downstairs Zone A (Around Cracked Zone)	21	12
	Downstairs Zone B (Uncracked/Sound Zone)	31	27
5.	Downstairs Zone A (Around Cracked Zone)	21	12
	Downstairs Zone B (Uncracked/Sound Zone)	31	27
6.	Downstairs Zone A (Around Cracked Zone)	21	12
	Downstairs Zone B	29	24

	(Uncracked/Sound Zone)		
7.	Downstairs Zone A (Around Cracked Zone)	21	12
	Downstairs Zone B (Uncracked/Sound Zone)	29	24
8.	Downstairs Zone A (Around Cracked Zone)	22	13
	Downstairs Zone B (Uncracked/Sound Zone)	29	24
9.	Downstairs Zone A (Around Cracked Zone)	21	12
	Downstairs Zone B (Uncracked/Sound Zone)	30	26
10	Downstairs Zone A (Around Cracked Zone)	21	12
	Downstairs Zone B (Uncracked/Sound Zone)	30	26

11.	Downstairs Zone A (Around Cracked Zone)	21	12
	Downstairs Zone B (Uncracked/Sound Zone)	29	24
12.	Downstairs Zone A (Around Cracked Zone)	21	12
	Downstairs Zone B (Uncracked/Sound Zone)	30	26

The test results clearly show that the concrete in and around the cracked regions had lower rebound values, leading to lower compressive strength, implying loss of surface integrity and possible micro-cracking below the surface. In contrast, the uncracked zones had higher rebound values, leading to high compressive strength, indicating relatively sound concrete.

These results are in agreement with those of Ojedele et.al, (2018), Akinbonmire (2022), Auta and Olanipekun (2025) who also repeated similar findings from their studies on structural integrity of reinforced concrete using rebound hammer.

4.3.2 Correlation Between Visual and Rebound Results

The visual inspection identified cracks likely due to shrinkage, corrosion, and stress concentrations, while the rebound hammer results quantitatively confirmed a reduction in surface strength in these same areas. The correlation between visible deterioration and lower rebound readings validates the accuracy of the field diagnosis.

4.3.3 Implication of Reduced Surface Strength

The reduced rebound numbers in the cracked areas indicate localized weakening of the concrete matrix, loss of adhesion between aggregate and cement paste, and potential ingress of harmful agents such as chlorides and sulphates (Anand, 2021). This emphasizes the need for not just cosmetic crack filling, but a restorative rehabilitation technique capable of sealing, bonding, and structurally stabilizing the affected zone.

4.4. Rehabilitation Plan

The rehabilitation plan below covers the full work flow of operation from inspection to hamdover, with objectives, materials and equipments, step-by-step procedures and the expected outcome.

Table 4.3: The Proposed Repair/Rehabilitation Plan to the specific Defects (Cracks) observed in the Buildings considered.

Steps	**Activities/ Stages**	**Objectives**	**Materials and Equipments**	**Procedures**	**Expected Outcome**
1.	Inspection and Crack Assessment	Identify and Classify cracks (Structural/ Non-Structural)	Crack guage, Rebound Hammer/UPV, Camera, Measuring tools.	Inspect and Record crack width, depth and pattern; determine repairable areas.	Crack Mapping Completed.

2.	Materials and Method Selection/ Design	Select bitumen type (grade/ emulsion), stitch bars size and spacing, injection pressure	Material data sheet, stitch bar specs, epoxy/cement grout	Show stitch layout, injection ports, calculate stitch spacing.	Materials and Method Selection Completed.
3.	Preparation of surface	Clean and prepare cracked surfaces for repair	Chisels, Wire brush, Air blower	Remove loose materials, dust and debris; ensure dry and sound substrate	Clean and Firm surface achieved.
4.	Design and Layout of Stitching	Plan and mark stitch positions for load transfer	Drill, Stitch bars, Grout/Epoxy	Drill holes across cracks at design spacing, insert and grout stitch bar	Proper alignment and Firm anchorage of stitches.
5.	Installation of Injection ports	Enable controlled injection of bitumen into cracks	Drill, Nozzle/Ports, Sealant	Fix injection ports along cracks line, seal crack surface except ports	Ports filled securely, no leakage.
6.	Bitumen Injection	Fill and Seal cracks to prevent water ingress	Bitumen (or emulsion), low	Heat bitumen (if required) and inject from	Crack fully filled with

			pressure pump, heater	lowest to highest port until filled	bitumen, no leakage.
7.	Grouting around stitch bars	Strengthen and Integrate stitched zones	Cementitious/ Epoxy grout, Trowel	Fill cavities and around stitches, finish surface smoothly	Surface sealed and Uniform finish obtained.
8.	Surface Protection	Provide waterproof and protective layer over repaired areas	Bituminous coating, Brush/Roller	Apply surface coating over repaired areas	Uniform coating and waterproof surface obtained.
9.	Inspection and Quality Check	Verify effectiveness of repair and sealing	Visual Inspection tools, Crack Monitoring tools	Check for continuity, no open cracks or leakage, ensure stitch integrity	Repair Completed and the specifications are adhered to.
10.	Documentation and Maintenance Plan	Record repair details and plan periodic monitoring	Inspection forms, Maintenance logs	Document materials used, locations repaired and schedule future checks	Documentation Completed.

Published work shows that bitumen (and bitumen emulsion) only, is effective primarily as a sealant and for pavement repairs, but when used alone it does not reliably restore structural tensile/flexural capacity of cracked concrete and is temperature-sensitive (Karimi et al., 2022/2023; Mignini et al., 2018).

Stitching (dowel bars / cross-stitching) is a recognized mechanical repair that restores load transfer and aggregate interlock across cracks when designed and installed properly (Pavement Preservation guidance, ~2010; Chen, D.H et.al, 2014). There is lack of knowledge on the combined use of bitumen injection and stitching for reinforced concrete structural members; therefore, the proposed combined method is theoretical, but must be validated experimentally. The expected advantage of combining them is complementary performance: stitching provides structural restoration while bitumen provides sealing and corrosion protection.

4.5. Summary of Findings

Based on the investigation conducted, the following key findings were identified:

1. Several types of cracks were observed on columns and walls, with crack widths ranging between 5 mm to 15 mm. The cracks were mostly vertical and diagonal, indicating causes such as shrinkage, thermal movement, reinforcement corrosion, settlement and structural stress concentration. In some areas, minor spalling and rust stains were observed, signifying potential moisture ingress and incipient corrosion of reinforcement.
2. The rebound hammer results showed lower rebound numbers in cracked regions (Zones A) compared to the uncracked/Sound (Zone B) areas. The estimated compressive strength of concrete near cracked zones was between 11–13 N/mm², while uncracked regions showed strengths up to 24–27 N/mm².

This confirmed localized reduction in surface hardness and integrity near the cracks, indicating that the cracks had affected both the mechanical strength and durability of the concrete surface.

3. Areas with visible cracks corresponded to low rebound readings, establishing a direct link between visual deterioration and mechanical weakness.

   The findings validated the use of rebound hammer testing as an effective diagnostic tool for assessing surface degradation before selecting appropriate repair methods.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

This chapter presents the summary of key findings, conclusions drawn from the investigation and testing carried out on cracked reinforced concrete columns and walls, and recommendations for effective repair and rehabilitation. The conclusions are based on the results of the visual inspection and non-destructive testing (rebound hammer test), as well as the proposed bitumen injection and stitching technique adopted for structural rehabilitation and durability enhancement.

5.1. Conclusions

Based on the results of the field inspection, non-destructive testing, and the proposed repair/rehabilitation plan, the following conclusions were drawn:

Crack defects in reinforced concrete buildings remain one of the most common structural problems, arising from various causes such as shrinkage, thermal stresses, corrosion of reinforcement, and structural overloading. These cracks, if left unattended, can compromise the durability and safety of the structure.

The visual and rebound hammer investigations confirm that crack defects significantly reduce the surface strength and durability of reinforced concrete members, thereby exposing the embedded reinforcement to possible corrosion and long-term deterioration.

The variation in rebound hammer values between cracked and uncracked zones indicates heterogeneous concrete strength, which implies the need for selective and targeted repair measures rather than general surface treatment.

The proposed repair/rehabilitation plan to the defect (cracks) identified in the buildings considered suggested the combined use of bitumen injection and stitching, since the sealing and waterproof properties of bitumen prevents the ingress of moisture, chlorides and other aggressive agents that causes corrosion of reinforcement and further deterioration. While stitching restores structural continuity across cracks by using steel or metallic dowels to transfer loads and prevents further propagation.

5.2. Recommendations

Based on the findings and conclusions from this theoretical study, the following recommendations are made:

1. Future research should conduct laboratory and field experiments to assess the actual structural and durability performance of the combined bitumen injection and stitching method under various conditions (temperature, load, and exposure).
2. Modified or polymerized bitumen with higher temperature stability and improved adhesion should be explored to enhance the performance of the injection component.
3. There is a need for guidelines and standard design charts for combined repair systems (bitumen + stitching) since existing codes primarily treat each method separately.
4. After rehabilitation, regular inspection and monitoring of repaired cracks should be carried out to ensure long-term effectiveness.
5. The use of eco-friendly and recyclable bituminous materials should be encouraged to minimize environmental impact.
6. Practicing engineers and maintenance personnel should be trained on modern combined rehabilitation methods, including bitumen injection and stitching, for effective application in existing building stock.

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C. Results from Rebound Hammer Test

Table C.1: Results from Rebound Hammer Test.

Site Location	Test Zones/Locations	Rebound Readings	Calculation of Average	Total Average	Compressive Strength (N/mm²)
1.	Downstairs Zone A (Around Cracked Surface)	22,24,23 21,18,26 19,20,21 23,18,19 24,24,24	69/3=23 66/3=22 60/3=20 60/3=20 72/3=24	109/5=22	11
	Downstairs Zone B (Uncracked/Sound Zone)	30,33,35 28,28,28 26,30,29 28,31,29 35,33,30	98/3=33 84/3=28 85/3=28 88/3=29 98/3=33	151/5=30	26
2.	Downstairs Zone A (Around Cracked Surface)	21,22,18 23,20,20 24,24,26 18,19,17 19,21,20	61/3=20 63/3=21 74/3=25 54/3=18 60/3=20	104/5=21	12
	Downstairs Zone B (Uncracked/Sound Zone)	25,27,28 33,29,30 35,33,36 26,25,28 30,28,29	80/3=27 92/3=31 104/3=35 79/3=26 87/3=29	148/5=30	26
3.	Downstairs Zone A (Around Cracked Surface)	18,20,22 17,20,18 21,21,21 23,22,24 20,25,22	60/3=20 55/3=18 64/3=21 69/3=23 67/3=22	104/5=21	12

	Downstairs Zone B (Uncracked/Sound Zone)	28,30,31	89/3=30	154/5=31	27
		25,28,26	79/3=26		
		35,33,36	104/3=35		
		38,36,33	107/3=36		
		26,27,28	81/3=27		
4.	Downstairs Zone A (Around Cracked Surface)	21,19,20	60/3=20	105/5=21	12
		23,22,24	69/3=23		
		18,19,20	57/3=19		
		24,21,20	65/3=22		
		22,19,23	64/3=21		
	Downstairs Zone B (Uncracked/Sound Zone)	35,32,33	100/3=33	154/5=31	27
		34,30,31	95/3=32		
		28,29,25	82/3=27		
		27,26,30	83/3=28		
		32,35,36	103/3=24		
5.	Downstairs Zone A (Around Cracked Surface)	21,19,18	58/3=19	105/5=21	12
		20,22,21	63/3=21		
		23,23,20	66/3=22		
		19,20,22	61/3=20		
		21,24,23	68/3=23		
	Downstairs Zone B (Uncracked/Sound Zone)	28,27,28	83/3=28	153/5=31	27
		33,31,30	94/3=31		
		26,25,27	78/3=26		
		35,33,33	100/3=33		
		37,35,34	106/3=35		
6.	Downstairs Zone A (Around Cracked Surface)	19,21,20	60/3=20	107/5=21	12
		23,20,22	65/3=22		
		21,18,20	59/3=20		
		24,23,22	69/3=23		
		21,25,19	65/3=22		
	Downstairs Zone B	27,26,27	80/3=27	146/5=29	24
		25,27,29	81/3=27		
		29,30,33	92/3=31		

	(Uncracked/Sound Zone)	35,32,31 26,28,30	98/3=33 84/3=28		
7.	Downstairs Zone A (Around Cracked Surface)	21,21,19 19,21,22 23,20,19 21,18,20 24,23,20	61/3=20 62/3=21 62/3=21 59/3=20 67/3=22	104/5=21	12
	Downstairs Zone B (Uncracked/Sound Zone)	25,26,28 32,29,30 27,30,32 35,33,31 26,28,29	79/3=26 91/3=30 89/3=30 99/3=33 83/3=28	147/5=29	24
8.	Downstairs Zone A (Around Cracked Surface)	18,21,24 19,21,20 22,24,20 23,22,21 24,21,23	63/3=21 60/3=20 66/3=22 66/3=22 68/3=23	108/5=22	13
	Downstairs Zone B (Uncracked/Sound Zone)	27,26,29 33,32,31 30,32,33 25,26,28 29,27,30	82/3=27 96/3=32 95/3=32 79/3=26 86/3=29	146/5=29	24
9.	Downstairs Zone A (Around Cracked Surface)	19,21,22 22,21,21 23,22,24 20,21,20 23,20,19	62/3=21 64/3=21 69/3=23 61/3=20 62/3=21	106/5=21	12
	Downstairs Zone B (Uncracked/Sound Zone)	25,26,27 29,30,32 33,34,31 28,30,29 34,32,31	78/3=26 91/3=30 98/3=33 87/3=29 97/3=32	150/5=30	26
10.	Downstairs	22,22,20	64/3=21	106/5=21	12

	Zone A (Around Cracked Surface)	19,21,23 23,20,22 18,21,23 22,20,21	63/3=21 65/3=22 62/3=21 63/3=21		
	Downstairs Zone B (Uncracked/Sound Zone)	31,34,32 28,27,30 30,29,31 25,28,29 30,31,34	97/3=32 85/3=28 90/3=30 82/3=27 95/3=32	149/5=30	26
11.	Downstairs Zone A (Around Cracked Surface)	22,20,19 21,23,18 20,22,21 24,22,20 21,23,25	61/3=20 62/3=21 63/3=21 66/3=22 68/3=23	107/5=21	12
	Downstairs Zone B (Uncracked/Sound Zone)	27,29,26 28,30,31 35,33,32 29,32,25 26,28,30	82/3=27 89/3=30 100/3=33 86/3=29 79/3=26	145/5=29	24
12.	Downstairs Zone A (Around Cracked Surface)	20,21,20 22,19,21 24,23,20 18,20,22 21,20,21	61/3=20 62/3=21 67/3=22 60/3=20 62/3=20	104/5=21	12
	Downstairs Zone B (Uncracked/Sound Zone)	25,27,26 30,29,32 28,31,33 34,32,30 29,28,31	78/3=26 91/3=30 92/3=31 96/3=32 88/3=29	148/5=30	26